



A Clean, Secure Nuclear Energy Solution for the 21st Century

Introduction

As the world grapples with the energy requirements of the future and the associated environmental concerns related to fossil fuels, nuclear energy is becoming increasingly viewed as a viable long-term solution. In the current state of “nuclear renaissance”, the large-scale adoption of nuclear power is being considered throughout the world. For this vision to become reality, a number of valid concerns have to be effectively addressed:

- The current commercial nuclear environment is characterized by large, complex projects that have excessive cost and extensive completion timelines.
- The complexity of these projects leads to an inherent variability in schedule that has a further impact on cost and timing.
- The complexity of the underlying nuclear technology requires an overly cumbersome licensing process that can take many years to complete.
- The widespread deployment of commercial nuclear technology is hindered by proliferation concerns that hinge on the limitations of the current technology and the configuration of the overall nuclear cycle.

Advanced Reactor Concepts, LLC (ARC) is a new company that addresses these challenges through the design of an innovative Small Modular Reactor (SMR) — the ARC-100 — and the definition of a comprehensive fuel cycle architecture that addresses the long-term energy security of customers and proliferation concerns of the rest of the world.

The ARC-100 Reactor

- **The ARC-100 reactor and its supporting fuel cycle provide a 21st Century solution for nuclear energy designed to meet the growing need for electricity in developing countries, as well as the imminent global need for carbon-free energy.** The ARC solution proposes to fully utilize the huge energy density of nuclear fuel, which is a million times that of fossil fuel, by incorporating a distributed fleet of small, fast reactors with a long refueling interval of 20 years. ARC-100 reactors provide localized energy services that are supported by a small number of centralized facilities handling fuel supply and waste management for the fleet (See Figure 1). The reactors are sized for local and/or small grids. They are standardized, modularized, and pre-licensed for factory fabrication and rapid site assembly. Their centralized fuel cycle infrastructure is sized for an economy of scale so that it may support a large fleet of reactors in the region while being operated under strict international safeguards.

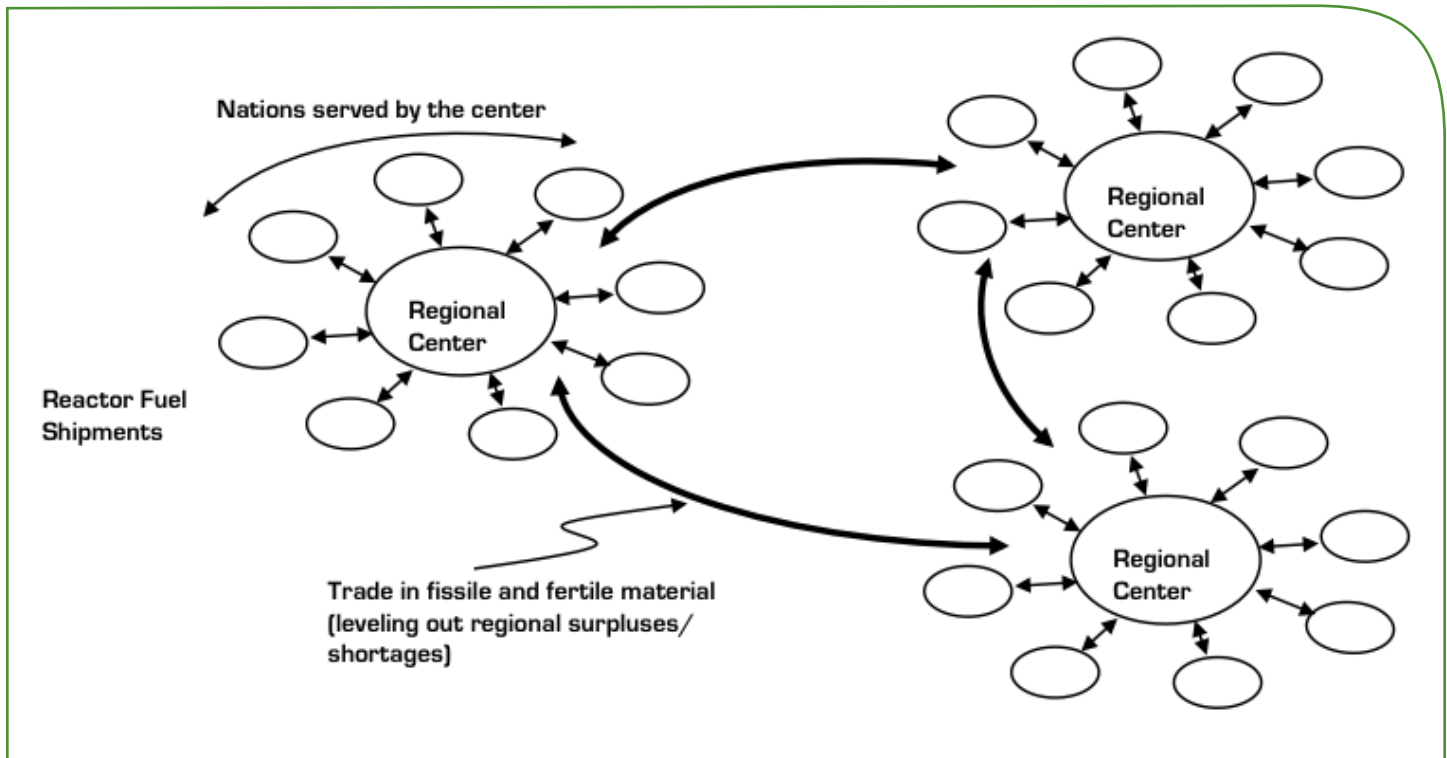


Fig. 1. Nuclear Energy Supply Architecture

- The ARC-100 is a 100 MWe (260 MWt), sodium-cooled fast reactor operating on a long, whole core-refueling interval of 20 years. Its initial fuel load is comprised of enriched uranium (with an enrichment level of <20%) in the form of metal alloy fuel in ferritic-cladding. The reactor exhibits an internal breeding ratio of near unity, such that its reactivity burnup swing is small and its core is fissile self-sufficient. It attains 80 to 100 MWtd/kg fuel average burnup, and upon pyrometallurgical recycling at the completion of its 20-year burn cycle, depleted uranium makeup feedstock is all that is required for core reload. Upon multiple recycles, the core composition shifts to an equilibrium transuranic (TRU) fuel composition which is also fissile self-sufficient and requires only U238 makeup upon recycle.



- **The reactor is intrinsically secure.** The reactor and its containment vessel are comprised of a steel guard vessel and dome positioned in a seismically isolated silo with a heavy shield structure. The silo and its shield control access to the reactor and protect the containment structures from external hazards.
- **The ARC-100 employs passive decay heat removal.** It provides a passive safety response to Anticipated Transients Without Scram (ATWS) and employs passive load follow. The balance of plant has no nuclear safety function; the reactor maintains itself in a safe configuration irrespective of any and all equipment failures, maintenance errors and operator mistakes occurring in the balance of plant.
- **The reactor is not equipped with fuel handling equipment.** Upon the completion of the 20-year burn cycle, an ARC team brings refueling equipment and replacement fuel assemblies to the reactor site. The original core is replaced with a new one and returned to the regional fuel cycle facility along with the refueling equipment.
- **There is no fuel storage facility at the reactor site for new or used fuel.** The derated specific power ($\text{kw}_t/\text{kg fuel}$) of the ARC-100 reactor, which allows a 20-year refueling interval within the proven burnup limit of metal alloy fuel, is low enough to permit fuel handling and shipment with only a very brief cooling period. Whole-core refueling is done within approximately 1.5 weeks of the reactor shutdown and used fuel is immediately shipped to the regional center so that no fuel cooling storage facilities are included in the plant design.

The ARC-100 Fuel Cycle

The ARC-100 is powered by a metal alloy fuel manufactured to incorporate a pyrometallurgical recycling process. The fuel and the recycling process were initially developed as part of the Integral Fast Reactor (IFR) project. Deployed reactors would be supplied with fuel utilizing the regional configuration as illustrated in Figure 1. With its extended refueling interval of 20 years, the ARC-100 based energy solution would provide the customer with long-term supply assurance while limiting access to nuclear fuel in the interest of global security. The complete fuel cycle for the ARC-100 is shown in Figure 2.



- Fission product removal is incomplete so that the fuel material is always highly radioactive before, during, and after recycling.
- All minor actinides remain with the plutonium so that the fuel material is always accompanied by strong heat and neutron emitting minor actinides in a TRU multi-isotope composition.
- The TRU product is admixed with uranium and fission products because the electrotransport process intrinsically carries some uranium with the TRU.



- All U and TRU are returned to the reactor to be fissioned. Only fission products go to the waste stream.
- All operations are performed in a shielded and inert cell environment because of the radioactivity of the fuel material.

The creators of the IFR pyrometallurgical recycling process and the traditional Plutonium-Uranium EXtraction (PUREX) reprocessing technique had different goals. The PUREX technique was developed as a by-product of weapons program specifically to produce high-purity weapons materials. In contrast, the IFR fuel cycle technique purposely uses a recycle technology that produces a recycle product useful for peaceful power production, but unsuitable for effective weapons use. An independent study jointly sponsored by the United States Department of State and the United States Department of Energy concluded that the IFR fuel recycling process is inherently more proliferation-resistant than the conventional PUREX recycling process and subsequent fabrication of oxide fuel pellets.

The ARC fuel cycle provides an inherent deterrent to nuclear proliferation by offering a customer unparalleled energy security in the form of a 20-year supply stored in an ARC-100 reactor core. In return, the customer is expected to participate in the regional fuel supply chain illustrated in Figures 1 and 2, with no direct access to fuel at any time. Additionally, this closed fuel cycle ensures an appropriate balance between a reactor's fissile consumption and the production of additional fissile material. The reactor generates replacement fuel only in the amount needed for the next cycle and burns up the initial fissile load, so that only fission products are produced as waste. Since no excess fissile material is generated, the proliferation hazard is minimized. In contrast, the current open fuel cycle associated with Light Water Reactors (LWR) produces an ever-growing inventory of fissile plutonium contained in the used fuel. This growing inventory requires perpetual safeguarding as the used fuel is initially stored in temporary storage pools, then subsequently transferred into final waste repositories.

The Inherent Security of the ARC Fuel Cycle

With the exception of the reactors themselves, the ARC fuel cycle consolidates the remainder of the fuel cycle facilities into regional centers where all fissile handling operations take place under continuous international oversight. This architecture stands in stark contrast to the alternative of widespread deployment of sensitive facilities in multiple nations where each would deploy an indigenous fuel cycle infrastructure for enrichment, fuel fabrication, reprocessing, and waste management/storage to ensure continual access to nuclear fuel.

The fuel of the ARC-100 is unattractive for weapons use at every link in the supply chain (Figure 2). The initial fuel load is metallic uranium alloy (U 10Zr) at an enrichment of <20%, making it unsuitable for weapons use. During the 20-year incore irradiation, the fuel attains a burnup of 8% by weight which burns out a fraction of the U235 and breeds in an equivalent mass of TRU, thus replacing a fraction of the U238. In addition, 8% by weight of highly radioactive fission products build into the fuel composition. This fuel composition is completely unsuitable for weapons use because of its fission product and U238 content, as well as its radiation level.



Upon shipment back to the regional fuel cycle center, the fuel undergoes pyrometallurgical recycling, a process in which the fission product removal is incomplete, TRU remains commixed with some U238 and U235, and all minor actinides remain intimately mixed with plutonium. The material composition remains unsuitable for weapons use across every step of the recycling process. The waste stream destined for waste storage and ultimate disposal is comprised only of fission products; heavy metal loss to waste is <0.1%.

The recycled U/TRU/fission product mixture is blended with 8% makeup U238 feedstock and alloyed with Zr for remote refabrication into a reload core, which is shipped directly to an ARC-100 reactor site for refueling. This material is also unsuitable for weapons use because of the predominance of admixed U238 and the minor actinides; the remaining fission products; and the intense radiation field from fission products and minor actinides.

The steps in this fuel cycle chain repeat indefinitely every 20 years. At no place in the chain is the fuel material suitable for direct weapons use. Over multiple cycles, the U235 content decreases while the TRU content both increases and shifts towards a more minor actinide heavy isotopic mix until (after ten or more recycles) an asymptotic TRU isotopic mix is reached. The curium and americium content of this asymptotic mix add further intrinsic radiation to the fuel thereby further extending its non-suitability for weapons use.

In its final asymptotic mix, the fuel cycle and the composition of material in the cycle are essentially those of the IFR. An extensive independent review of the IFR fuel cycle was conducted, and it was found to have significant nonproliferation advantages over aqueous-based closed cycles. Likewise, the composition of the fuel at various points in the cycle were declared by United States weapons designers to be unsuitable for weapons use without further processing.

Material containing fissile mass is present at every link in the supply chain (Figure 2). In the proposed ARC architecture, the fissile content is present:

- at extremely low concentrations in the resource harvesting and the waste management/storage links at the beginning and ending of the chain;
- in decladded “bulk” form only in the enrichment, fuel fabrication, reprocessing, and fuel re-fabrication links of the chain — *all of which are conducted at regional fuel cycle centers rather than onsite*;
- in enclosed, discrete fuel element “items” during the shipment and in-reactor irradiation links in the supply chain.



Furthermore, access to fissile mass is severely constrained in every link:

- Its low concentration in inert material requires extensive processing to harvest useful amounts.
- The fuel cycle site and its facilities are protected by extensive levels of onsite physical security and barriers (guns, guards, and gates) that would most likely be backed by massive, offsite, rapid-response, protective forces.
- During in-reactor residence, the material is inaccessible. There is no onsite refueling equipment, no fuel storage pools exist, and the vessel is housed in its protective silo.
- For shipment of the first core loading, the material is uranium at <20% enrichment, which is not usable for weapons production in any case.
- During shipment of new and used fuel after the first loading, access to the material inside the shipping casks would be deadly due to its high radiation field.

Moreover, the “time at risk” profile for the cycle is heavily constrained. For 20 years, the fuel is inaccessible inside the reactor; then for a subsequent two years, it is in the confines of the heavily guarded and monitored regional center. During transit between the reactor and the regional center, the fuel is contained in a bulky shipping cask, is highly radioactive, and is constantly tracked and monitored via satellite.

Conclusion

The long-term viability of nuclear power as a source of clean, sustainable energy requires the implementation of a fundamentally different underlying technology. The current focus on large reactors has serious limitations which inhibit the development of the commercial nuclear market. At the same time, a new, effective fuel-cycle architecture is required to address the legitimate proliferation concerns associated with the widespread deployment of nuclear technology. ARC addresses these concerns with a comprehensive solution that incorporates the ARC-100, an SMR based on innovative technology, and an associated secure, closed fuel-cycle. This solution will satisfy the growing energy needs of the 21st century and will fully deliver on the promise of safe nuclear energy.

Advanced Reactor Concepts, LLC
11710 Plaza America Drive, Suite 2000
Reston, VA 20190
703.871.5226 (P)
703.871.5227 (F)
info@arcnuclear.com
www.arcnuclear.com